Controlled Atmosphere Storage

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Introduction: Controlled atmosphere (CA) storage involves altering and maintaining an atmospheric composition that is different from air composition (about 78% N_2, 21% O_2, and 0.03% CO_2); generally, O_2 below 8% and CO_2 above 1% are used. Atmospheric modification should be considered as a supplement to maintenance of optimum ranges of temperature and RH for each commodity in preserving quality and safety of fresh fruits, ornamentals, vegetables, and their products throughout postharvest handling. This chapter gives an overview of responses to CA; specific CA considerations are in individual commodity summaries.

Biological Bases of CA Effects: Exposure of fresh horticultural crops to low O_2 and/or elevated CO_2 atmospheres within the range tolerated by each commodity reduces their respiration and ethylene production rates; however, outside this range respiration and ethylene production rates can be stimulated indicating a stress response. This stress can contribute to incidence of physiological disorders and increased susceptibility to decay. Elevated CO_2-induced stresses are additive to, and sometimes synergistic with, stresses caused by low O_2; physical or chemical injuries; and exposure to temperatures, RH, and/or ethylene concentrations outside the optimum range for the commodity.

The shift from aerobic to anaerobic respiration depends on fruit maturity and ripeness stage (gas diffusion characteristics), temperature, and duration of exposure to stress-inducing concentrations of O_2 and/or CO_2. Up to a point, fruits and vegetables are able to recover from the detrimental effects of low O_2 and/or high CO_2 stresses (fermentative metabolism) and resume normal respiratory metabolism upon transfer to air. Plant tissues have the capacity for recovery from the stresses caused by brief exposure to fungistatic atmospheres (> 10% CO_2) or insecticidal atmospheres (< 1% O_2 and/or 40 to 80% CO_2). Post-climacteric fruits are less tolerant and have lower capacity for recovery following exposure to reduced O_2 and/or elevated CO_2 levels than pre-climacteric fruits. The speed and extent of recovery depend upon duration and levels of stresses, and underlying, metabolically driven cellular repair.

Elevated-CO_2 atmospheres inhibit activity of ACC synthase (key regulatory site of ethylene biosynthesis), while ACC oxidase activity is stimulated at low CO_2 and inhibited at high CO_2 concentrations and/or low O_2 levels. Ethylene action is inhibited by elevated CO_2 atmospheres. Optimum atmospheric compositions retard chlorophyll loss (green color), biosynthesis of carotenoids (yellow and orange colors) and anthocyanins (red and blue colors), and biosynthesis and oxidation of phenolic compounds (brown color). Controlled atmospheres slow down the activity of cell wall degrading enzymes involved in softening and enzymes involved in lignification leading to toughening of vegetables. Low O_2 and/or high CO_2 atmospheres influence flavor by reducing loss of acidity, starch to sugar conversion, sugar interconversions, and biosynthesis of flavor volatiles. When produce is kept in an optimum atmosphere, retention of ascorbic acid and other vitamins results in better nutritional quality.

Severe stress CA conditions decrease cytoplasmic pH and ATP levels, and reduce pyruvate dehydrogenase activity while pyruvate decarboxylase, alcohol dehydrogenase, and lactate dehydrogenase are induced or activated. This causes accumulation of acetaldehyde, ethanol, ethyl acetate, and/or lactate, which may be detrimental to the commodities if they are exposed to stress CA conditions beyond their tolerance. Specific responses to CA depend upon cultivar, maturity and ripeness stage, storage temperature and duration, and in some cases, ethylene concentrations.

N_2 is an inert component of CA. Replacing N_2 with argon or helium may increase diffusivity of O_2, CO_2 and C_2H_4, but they have no direct effect on plant tissues and are more expensive than N_2 as a CA component.

Super-atmospheric levels of O_2 up to about 80% may accelerate ethylene-induced degreening of non-climacteric commodities and ripening of climacteric fruits, respiration and ethylene production rates, and incidence of some physiological disorders (such as scald on apples and russet spotting on lettuce). At levels above 80% O_2 some commodities and postharvest pathogens suffer from O_2 toxicity. Use of super-atmospheric O_2 levels in CA will likely be limited to situations in which they reduce the negative effects of fungistatic, elevated CO_2 atmospheres on commodities that are sensitive to CO_2-injury.

Beneficial Effects of CA (optimum composition for the commodity):
Retardation of senescence (including ripening) and associated biochemical and physiological changes, ie., slowing down rates of respiration, ethylene production, softening, and compositional changes.
Reduction of sensitivity to ethylene action at O_2 levels < 8% and/or CO_2 levels > 1%.
Alleviation of certain physiological disorders such as chilling injury of avocado and some storage disorders, including scald, of apples.
CA can have a direct or indirect effect on postharvest pathogens (bacteria and fungi) and consequently decay incidence and severity. For example, CO_2 at 10 to 15% significantly inhibit development of botrytis rot on strawberries, cherries, and other perishables.
Low O_2 (< 1%) and/or elevated CO_2 (40 to 60%) can be a useful tool for insect control in some fresh and dried fruits, flowers, and vegetables; and dried nuts and grains.

Detrimental Effects of CA (above or below optimum composition for the commodity):
Initiation and/or aggravation of certain physiological disorders such as internal browning in apples and pears, brown stain of lettuce, and chilling injury of some commodities.
Irregular ripening of fruits, such as banana, mango, pear, and tomato, can result from exposure to O_2 levels below 2% and/or CO_2 levels above 5% for > 1 mo.
Development of off-flavors and off-odors at very low O_2 concentrations (as a result of anaerobic respiration) and very high CO_2 levels (as a result of fermentative metabolism).
Increased susceptibility to decay when the fruit is physiologically injured by too-low O_2 or too-high CO_2 concentrations.

Commercial Application of CA Storage: Several refinements in CA storage have been made in recent years to improve quality maintenance; these include creating nitrogen by separation from compressed air using molecular sieve beds or membrane systems, low O_2 (1.0 to 1.5%) storage, low ethylene (< 1 μL L^{-1}) CA storage; rapid CA (rapid establishment of optimal levels of O_2 and CO_2, and programmed (or sequential) CA storage, eg., storage in 1% O_2 for 2 to 6 weeks followed by storage in 2 to 3% O_2 for the remainder of the storage period. Other developments, which may expand use of atmospheric modification during transport and distribution, include improved technologies of establishing, monitoring, and maintaining CA, using edible coatings or polymeric films with appropriate gas permeability to create a desired atmospheric composition around and within the commodity. MAP is widely used in marketing fresh-cut produce.

Applications of CA to cut flowers are very limited because decay caused by *Botrytis cinerea* is often a limiting factor to postharvest life, and fungistatic CO_2 levels damage flower petals and/or associated stem and leaves. Also, it is less expensive to treat flowers with anti-ethylene chemicals than to use CA to minimize ethylene action.

Commercial use of CA storage is greatest on apples and pears worldwide; less on cabbages, sweet onions, kiwifruits, avocados, persimmons, pomegranates, and nuts and dried fruits and vegetables (Table 1). Atmospheric modification during long-distance transport is used on apples, asparagus, avocados, bananas, broccoli, cane berries, cherries, figs, kiwifruits, mangos, melons, nectarines, peaches, pears, plums, and strawberries. Continued technological developments in the future to provide CA during transport and storage at a reasonable cost (positive benefit/cost ratio) are essential to greater applications on fresh horticultural commodities and their products.

Table 1. Classification of horticultural crops according to their CA storage potential at optimum temperatures and RH.

Storage Duration (mo)	Commodities
> 12	Almond, Brazil nut, cashew, filbert, macadamia, pecan, pistachio, walnut, dried fruits and vegetables
6 to 12	Some cultivars of apples and European pears
3 to 6	Cabbage, Chinese cabbage, kiwifruit, persimmon, pomegranate, some cultivars of Asian pears
1 to 3	Avocado, banana, cherry, grape (no SO_2), mango, olive, onion (sweet cultivars), some cultivars of nectarine, peach and plum, tomato (mature-green)
< 1	Asparagus, broccoli, cane berries, fig, lettuce, muskmelons, papaya, pineapple, strawberry, sweet corn; fresh-cut fruits and vegetables; some cut flowers

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